Multiwavelength Observations of Tidally Induced Star Formation in the M81 Group

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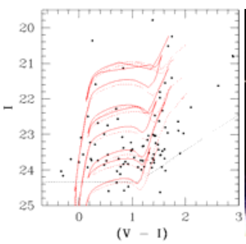
Abstract

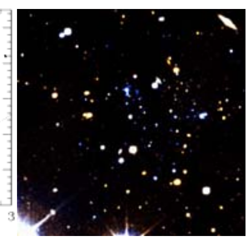
We combine optical, infrared, and millimeter/submillimeter-wave observations to study a small clump of recently formed stars and the interstellar environment between the galaxies of M81 and NGC 3077. This clump is coincident with an HI emission knot in the Southern Tidal Arm of the M81 system, and is known to have formed stars as recently as 30-70 Myr ago; long after the interactions that created the HI arm. This object is about 1 kpc in extent, and is considered a tidal dwarf (TD) candidate. To better characterize its star forming environment, we place limits on the molecular gas and dust content of this potential TD object, and compare its properties to well-studied star forming regions. The infrared observations were obtained as part of the Spitzer Space Telescope Research Program for Teachers and Students, so these data are also being used for educational purposes by teachers and students across the US.

Introduction & Background

Between 220 and 280 million years ago, tidal encounters between M81, M82, and NGC 3077 liberated streams of HI gas (van der Hulst 1979; Appleton et al 1981; Yun, Ho, & Lo 1994, Yun 1999). These streams appear as a network of HI bridges dotted by small dwarf galaxies (Karachentseva et al 1985, Karachentsev et al 1985). Since some of these dwarfs contain stars that are significantly younger than the interaction age of the system, it is possible that they formed from material stripped from galactic outskirts (Makarova et al 2002). **Here we present multiwavelength observations (including broadband optical images, Hα observations, IR Spitzer (IRAC 8 μm) data, & molecular line (CO) observations) of two previously undiscovered tidal dwarf candidates in the M81 Group and attempt to characterize the nature of their stellar and molecular environments**. The proximity of the M81 Group, and the relative isolation of TD1, makes this object an ideal laboratory for the study of the tidal dwarf galaxy phenomenon.

Optical Imaging & CFHT Results

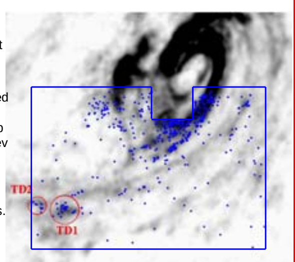




Left: Color-Magnitude Diagram of stars in the TD1 region. Solid lines denote Z=0.004 isochrones (with ages 25, 50 and 100 Myr, from top to bottom) from Girardi et al.(2002), and dotted lines represent the same models with Z=0.008. $(m\text{-}M)_I$ = 28.1 and E(V-I)=0.15 have been applied to both sets of models. Dashed lines denote the 50 % completeness level for the CFHT photometry.

Right: Color image of TD1 from the CFHT data (DeCesar et al 2004). Image is 2.5'x2.5', or ~3 kpc at the distance of M81 (3.25 Mpc, Tamman & Sandage 1968).

- CFHT (CFH12K camera) survey data show "blue" (A and F-type) supergiants scattered throughout group (DeCesar et al 2003, see also Durrell et al 2004).
- Southeast of M81 are two isolated blue clumps (TD1 & TD2). They are **not part** of the Arp Loop (Arp 1982), the Garland (Karachentsev et al 1985) or a previously cataloged feature.
- Systems are ~ 2 kpc in extent, and coincide with dense HI knots.
- A CMD of the stars in TD1 ($\sim 10^6$ L_{SUN}) shows that they are anywhere from ~25 to ~100 Myr old.
- Last tidal encounter between M81 and NGC 3077 occurred ~250 Myr ago (Yun, Ho, & Lo 1994; Yun 1999). **This is likely in situ in intergalactic environment.**

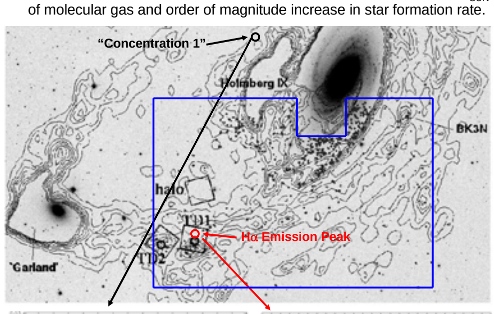


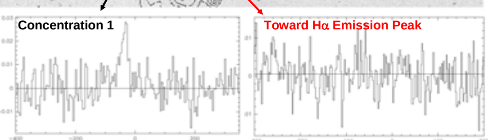
Above: Blue star ($(V\text{-}I)_O$ < 0.25) distribution in CFHT field (outlined by blue box), superimposed on the HI map of Yun et al (1994). Less than 10% of the objects are likely to be background contamination (based on a control field CMD).

Hα and CO (J=2-1) & (J=1-0) Observations

We have used the ARO 10m (HHT) and 12m telescopes and the VATT 1.8 m telescopes on Mt. Graham & Kitt Peak, AZ to probe the cold/warm (~5 – 15 K) molecular and hot, ionized environments. Images (1 hr total exposure) were made with a CCD camera and narrowband Hα filter at the VATT. Spectral line observations of CO (J=2-1) and (J=1-0) were made at the HHT and 12m telescopes, respectively. A summary of the observational results are presented.

- **Results of Hα Image Analysis:**
  - Hα emission detected in the vicinity of young, blue star in TD1; The presence of H-alpha in TD1 provides a stronger case for a young population of stars in this region. Supports *in situ* formation hypothesis & results of the CFHT survey.
  - *Luminosity (Hα) =* 8.0×10^{37} L_{SUN}. The H-alpha luminosity of TD1 is smaller than various HII regions measured in the tidal debris of major mergers (Hibbard 1995), but similar to lower luminosity regions in the Eastern tail of minor merger NGC 2782 (Smith et al. 1999).
  - *Star Formation Rate =* 6.3×10^{-4} M_{SUN}/yr
  - *Ionizing Photon Rate,* $Q(H^0) = 5.8 \times 10^{49}$ *photons/sec*
- **Results of CO Analysis:**
  - Using CO (J=1-0) and (J=2-1), limits were placed on the molecular mass within the telescope beam toward Tidal Dwarf candidates.
  - Linewidth-cloud size relation of Galactic Giant Molecular Clouds. Assumptions: clouds are in virial equilibrium, gravitationally bound, same metallicity, temperature and density as Milky Way clouds: **$N(H_2)$ [cm^{-2}] = 2.3×10^{20} * I_{CO} [K km/s]** (Strong et al 1988) where I_{CO} is the total CO integrated intensity.
  - *Molecular Gas Limit Toward TD1: <* 1.4×10^7 M_{SUN}*; Limit Toward Peak of Hα emission: <* 4.6×10^6 M_{SUN}.
  - **Beam dilution may be a problem** (size of 12m beam at 115 GHz ~ 1' and size of SMT beam at 230 GHz ~ 33"). Observations with millimeter and submm interferometers would shed new light (e.g., Walter, Martin, & Ott 2006).
  - **Comparing to other Tidal Environments:** TD1 molecular mass limits are lower than the Western tidal tail of NGC 2782 taken with OVRO (< 6×10^6 M_{SUN}, Braine et al. 2001). Comparing to a tidal region near NGC 3077 (also within the M81 group), Walter, Martin, and Ott (2006) find 10^7 M_{SUN} of molecular gas and order of magnitude increase in star formation rate.



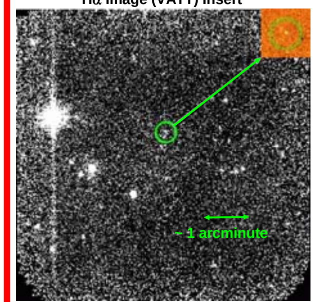


Top: *Digital Sky Survey image* (80' wide, 50' high) of the M81 galaxy cluster including M81 (northwest), NGC 3077 or the Garland (southeast), and Holmberg IX (east of M81). *Contours denote* the HI bridges observed by Yun et al 1999, the *blue box* shows the location of the CFHT field, and *filled dots* indicate the blue stars (Durrell et al – see left panel). Boxes show locations of Tidal Dwarf candidates & *dark open circles* (~1' diameter) show positions of HHT & 12m spectral line observations. "Concentration 1" (detection verified our observing strategy; originally observed by Brouillet et al 1992) and the Hα emission peak are indicated.

Bottom: Deep observations were made toward ~9 separate pointings near Tidal Dwarf regions in CO (J=1-0) and (J=2-1). CO (J=1-0) observations toward "Concentration 1" **(left)** and the Hα peak **(right)** are shown for reference (rms achieved was 2 mK and 1 mK, respectively).

Spitzer Observations and Results

Spitzer 8 μm IRAC Image with Hα Image (VATT) Insert

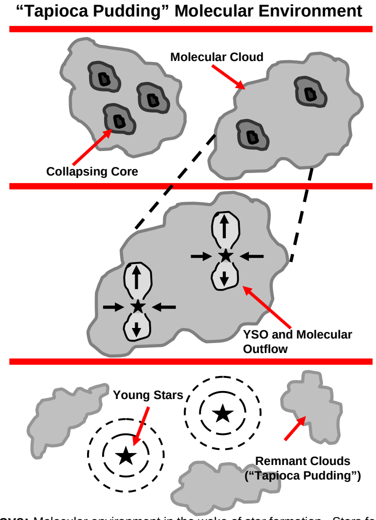


- **IRAC 8 μm Image:** exposure time = 144 sec, field of view = ~6'x6', shows warm dust by tracing 8 μm PAH feature.
- **Hα Image:** exposure time = 1 hour total
- **Preliminary Results:**
  - Hα emission *coincides* with 8 μm IRAC emission
  - Supports interpretation of in-situ star formation in Tidal Dwarf candidates
  - More time with Spitzer (IRAC & MIPS) would help verify this result.

Summary and Ongoing / Future Work

- A CMD of the stars in TD1 clump shows they are anywhere from ~25 to ~100 Myr in age (younger than last tidal encounter between M81 and NGC 3077). Stars have likely formed *in situ* in the intergalactic environment
- Hα emission is *coincident* with 8 μm emission seen by IRAC – supports *in situ* star formation theory.
- Follow up Spitzer observations (IRAC & MIPS) would help strengthen this work.
- Absence of CO emission from Tidal Dwarf regions means that either the molecular gas has been completely disrupted into HI or H^+ OR that the molecular hydrogen still exists but the carbon is no longer CO, but instead C and C+ (see "Tapioca Pudding" model below).
- Follow-up observations with new mm and submm interferometers may help (e.g., CARMA, SMA).
- Ongoing analysis of PISCES narrowband infrared images (Bok Telescope) will provide a picture of the hot molecular gas component, searching for UV pumped 2.12 μm H_2 emission at molecular cloud edges.
- Disrupted "tapioca" molecular clouds would be thin and granular, mostly H_2 but with little or no CO (like a PDR). Our infrared H_2 measurements can help constrain whether this 'tapioca' model well describes the environment.

"Tapioca Pudding" Molecular Environment



Above: Molecular environment in the wake of star formation. Stars form in overdense regions (cores) of molecular clouds that become unstable to collapse. While forming, stars accrete molecular material & drive energetic outflows. The energy input by forming stars and ionizing photons/energetic winds from hot, young stars can disrupt the parent molecular environment (e.g., Elmegreen 1986), resulting in remnant "Tapioca Pudding".

Acknowledgements

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